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4 authors, including:

Masashi Hayakawa
University of Electro-Communications

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Results of ultra-low-frequency magnetic field measurements during the Guam earthquake of 8 August 1993

Masashi Hayakawa[1], Ryusuke Kawate[1], Oleg A. Molchanov[1], and Kiyohumi Yumoto[2]

Abstract. We report the results of measurements of ultra-low-frequency magnetic noise during a large earthquake (Ms=7.1) at Guam of 8 August, 1993 (depth ~ 60 km). The ULF observing system is located in the Guam Island, about 65 km from the epicenter. Several distinct features of this analysis are summarized. (1) We have proposed rather sophisticated statistical analyses (monthly mean, standard deviation) in order to estimate the wave intensity and polarization (i.e. ratio Z/H). (2) A comparison between the ULF wave activity and ΣKp, is useful in distinguishing between the space geomagnetic pulsations and non-space emissions. (3) Then, the use of the ratio (Z/H) is found to be of essential importance in discrimating the emissions presumably of seismic origin from space plasma waves. (4) The statistical analysis of the temporal evolution of this ratio, has yielded that it shows a broad maximum only about one month before the earthquake, and this suggests that the emissions during this period are very likely to be magnetic precursors. (5) The temporal variation of Z component is similar to that for the Loma Prieta earthquake such that it shows a broad maximum ten days ~ two weeks before the earthquake and another increase a few days before the earthquake. (6) The emissions presumably associated with the earthquake are of noise-like nature, and their main frequency is 0.02 ~ 0.05 Hz (with maximum intensity ~ 0.1 nT).

Introduction

Electromagnetic phenomena in a wide frequency range from DC to HF have been recognized as precursors to earthquakes (and volcano eruptions) [e.g., Hayakawa and Fujinawa, 1994]. Historically there had been extensive attention to the seismogenic emissions in the comparatively higher frequencies, ELF/VLF/LF range and also to the DC electric and magnetic field variations. Of course, the studies in these frequency ranges are still being continued [see Hayakawa and Fujinawa, 1994].

It has recently been found that there have been observed earthquake precursor signals in the ULF ($f<$ 10Hz) range [Kopytenko et al., 1990; Fraser-Smith et al., 1990; Bernardi et al., 1991; Molchanov et al., 1992]. The results by these authors are based on the ULF magnetic field measurements for the two large earthquakes (Spitak and Loma Prieta), and Molchanov et al.[1992] have compared the ULF characteristics for these earthquakes, who have found many similarities between these two earthquakes. Though, Mueller and Johnston (1990) have not found any quasi-steady magnetic field changes in the frequency range of $f< 10^{-3}$Hz for the Loma Prieta earthquake. Since these ULF results may be a promising candidate for short-term predictor of earthquakes, we are in a position that we should accumulate more amount of convincing ULF signatures of earthquakes. Recently, Kopytenko et al.(1994) have presented additional evidence on the ULF signatures for nearby moderate earthquakes, but Fraser-Smith et al.(1994) have found no large signals that could be associated with the Northridge earthquake (M=6.7) because their measurements have been made at locations probably too far from the epicenter for signals to be observed. The purpose of the present report is to provide much more confidence on the presence of ULF precursor activity on the basis of the analysis results of ULF magnetic field measurements for the Guam earthquake.

[1] The University of Electro-Communications, Chofu Tokyo, Japan
[2] STE Laboratory, Nagoya University, Toyokawa Aichi, Japan

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Experimental Results

On 8 August,1993 at 8:34 UT a comparatively large earthquake (Ms=7.1) occurred "suddenly and without any foreshock and aftershock activity (with magnitude greater than 5.0)" near the Guam Island; its epicenter was located in the sea at the geographic coordinates (12.98°N, 144.80°E) and its depth was 60km. At the time of this earthquake,ULF magnetic field measurements were being carried out at the Guam observatory (geographic coordinates: 13.58°N, 144,87°: geomagnetic coordinates: 9.02°N, 225.15°E;L=1.03), which is located about 65 km from the epicenter.

The ULF magnetic field measurements were made with a three-axis ring-core-type fluxgate magnetometer with the data logger system and a time signal generator. The three field components (H(NS), D(EW) and Z(vertical)) are recorded on a digital cassette type with a sampling rate of 1sec, which means that the upper analyzable frequency must be about ~ 0.4Hz. See Yumoto et al. (1992) for more details of the measuring system. The data for this report cover the interval from 1 April to 30 October 1993.

Our preliminary analysis of the diurnal variation of ULF wave activity has revealed that the data at day are much more variable than those at night as was found by Saito (1969), and so we have chosen the midnight period of 4 hours from L.T. = 22h to 2h (L.T.=U.T. +10h at Guam) for further detailed analyses. Since the time period covers two successive days in L.T., the date in the following discussion is defined as the earlier day. The waveforms of three field components during each interval of 30 minutes, are subjected to an FFT analysis (the frequency resolution is 4.9×10^{-4}Hz), and the data for one day consist of eight frequency spectra during such 30 min. intervals. The frequency spectrum of the intensity for each 30 min. interval is compared with the monthly average (m) which is estimated by using all the frequency spectra in the relevant month. Also, the standard deviation (σ) is simultaneously estimated.

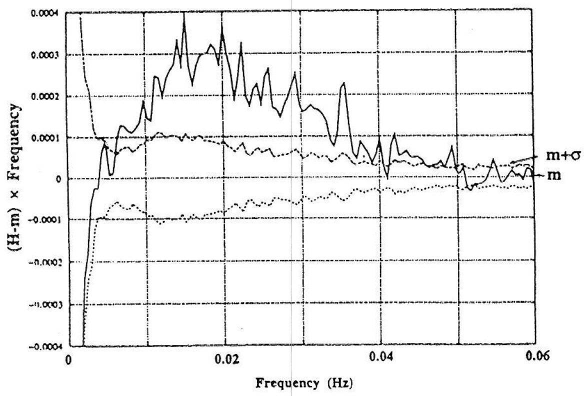

Figure 1. An example of analysis procedure. A typical frequency spectrum of H component on a particular day (8 June). The intensity is expressed in the form of (H-m)frequency (m; monthly mean) and σ is standard deviation.

Fig.1 illustrates one typical example on a particular day (8 June), and this is the frequency spectrum (for H component) averaged by using the eight spectra on this day. The level 0 in the figure means the monthly average (m) and the dashed lines indicate m+ σ and m- σ. We see from this figure that the H component is very intense in the frequency range lower than 0.04 Hz and it even exceeds m +2 σ in the frequency range from 0.02 to 0.03 Hz on this day. The frequency below 0.01 Hz is quasi-DC, which is not our interest, and we notice the lack of sensitivity of the measuring system in the frequency range above 0.1 Hz. So, our emphasis is placed on the frequency range between 0.01 Hz and 0.1 Hz. We will not deal with D component, because its variation is nearly the same as that for H component.

Fig.2 illustrates the temporal evolution of ULF wave activity during the whole period (unfortunately no measurement after the earthquake to 17 September), together with that of geomagnetic activity expressed by ΣKp (daily sum of 3 hr Kp index). We have defined the index of ULF wave activity in the following way. By looking at the intensity frequency spectrum on every day (as in Fig.1), we estimate the occurrence frequency of the wave peaks exceeding m+σ for both components (H and Z) in the frequency range from 0.01 to 0.05 Hz. The criterion of being active or very active is whether the bandwidth over which the intensity exceeds m+σ, is less than or greater than one half the above frequency bandwidth (0.01 - 0.05 Hz). Index 1 indicates that either one or both of the two components is active, and

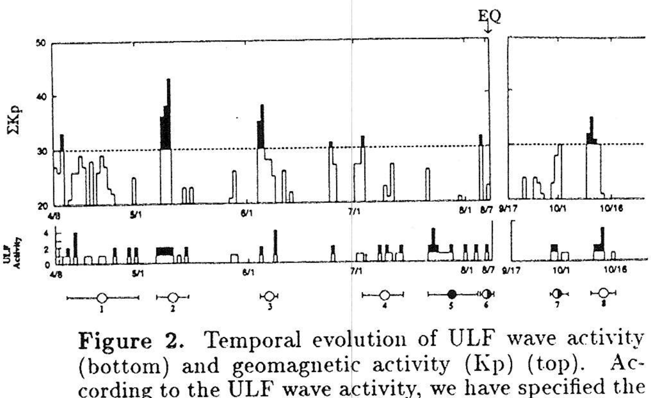

Figure 2. Temporal evolution of ULF wave activity (bottom) and geomagnetic activity (Kp) (top). According to the ULF wave activity, we have specified the intervals, 1-8. ○ refers to the interval closely related to the geomagnetic activity, ● indicates the interval not associated with geomagnetic activity (supposedly earthquake-related), and ◑ indicates the interval for which it is difficult to attribute it to either one of the above two cases.

Index 2 means that either one component is very active. While, Index 4 corresponds to the situation that both of the two components are very active. Based on the combined consideration of the geomagnetic activity and ULF wave activity in Fig.2, we have specified the time intervals, 1 to 8. High ULF activity during the intervals of 1, 2, 3, 4 and 8 is found to be clearly associated with the corresponding high geomagnetic activity. Possible ULF waves around midnight and in this frequency range are Pi2 and Pc4 (Saito, 1969), which are known to closely related with geomagnetic activity such that they tend to occur on the day of ΣKp peak and persist for a few successive (Saito, 1969). While, the period 5 is geomagnetically extremely quiet, but we find high wave activity. This means that this ULF wave activity is not related to geomagnetic activity, but might be associated with any other effect (might be earthquake-related). While, the situation for the intervals 6 and 7 is different from the above-mentioned intervals; we have two ULF activities before and after the peak in ΣKp. As is understood from the above-mentioned intervals, the high geomagnetic activity induces high ULF activity simultaneously on the same day with a peak in ΣKp and afterwards (or with some delay of the order of a few), but we notice ULF activity before the peak in ΣKp, which is difficult to understand as a geomagnetic effect. Hence, it may be possible that these two intervals are a combination of the geomagnetic (space plasma waves) and non-geomagnetic consequences.

Fig.3 illustrates the temporal variation of the two components (Z and H) during the whole period. The intensity is integrated over four hours for each day in the same frequency range, and the intensity on each day is the average over ± 2 days around that day. Fraser-Smith et al. (1990) presented the intensity of only the Z component for the Loma Prieta earthquake, before which the geomagnetic activity was quiet. However, the temporal behaviors (H and Z) as in Fig.3 cannot provide us with any essential features on seismogenic emissions, without any close comparison with ΣKp variation. Of course, the geomagnetic activity was rather quiet during the period from the middle of July to the main shock. So that, the variation of Z component during this period might reflect the temporal behavior of ULF earthquake signature, because its temporal variation in Fig.3 is seen to be very similar to that for the Loma Prieta earthquake by Fraser-Smith et al. (1990).

Since it is not so easy to find some special features in Fig.3, we need some idea, which is the estimation of the wave origin by using the polarization, or the parameter of Z/H. Molchanov et al.(1992) and Kopytenko et al. (1994) have indicated that this ratio must be a key in distinguishing between the geomagnetic pulsa-

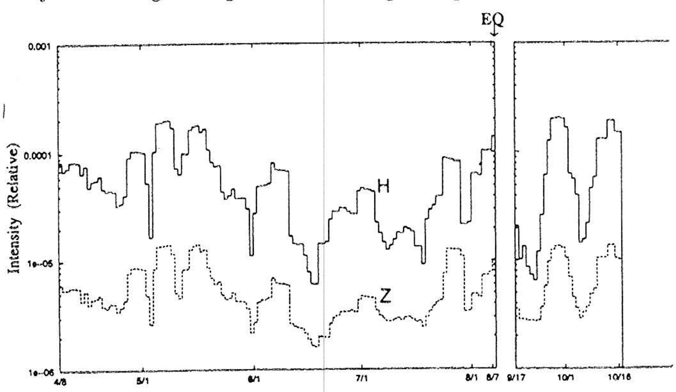

Figure 3. Temporal evolution of H (full line) and Z (broken line) components during the whole period. The intensity integrated over the frequency range, 0.01 ~ 0.05 Hz is plotted, and 5 days running mean is used.

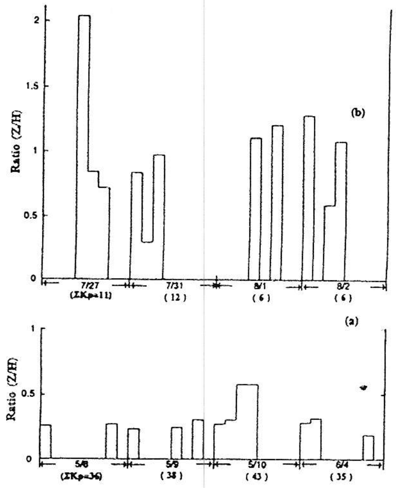

Figure 4. The ratio (Z/H) of the emissions whose H and Z exceed the corresponding m+σ. Each day consists of eight data of 30min. interval. (a) High and (b) low geomagnetic activity.

tions of ionospheric /magnetospheric origin and seismogenic emissions, Fig.4 illustrates the characteristics of this ratio during low (b) (during the interval 5) and high (a) (during the intervals 1 and 2) geomagnetic activities. One day result consists of 8 values, each value corresponding to the fundamental interval of 30 minutes. When there are wave intensities in the frequency range of 0.01 to 0.05 Hz whose Z and H components exceed the corresponding m+ σ, we evaluate the ratio (Z/H) over those frequency ranges and we average the values, which is plotted as a value for that 30 min. interval. Four are tentatively chosen for the quiet (b) condition whose ΣKp is less than 12 and which is supposedly seismogenic period, and four with high activity (Σ K $\geq$ 35). This figure suggests the most compelling implication that the ratio of Z/H of the emissions considered to be space waves during high geomagnetic activity is extremely small, on the order of 0.2 $\sim$ 0.3, while that during the very quiet (Fig.4(b)) is obviously different from the former such that the ratio is much larger than in Fig.4(a), and it exceeds 1.0 on some occasions. This kind of peculiarity was suggested for seismogenic emissions by Kopytenko et al.(1994), and it is possible that these emissions are associated with earthquakes(or earthquake signatures).

Fig.5 illustrates the temporal evolution of the ratio, Z/H during the whole period. The value for each day is the average value of the ratio running during 5 days, and the general tendency is given in a full line based

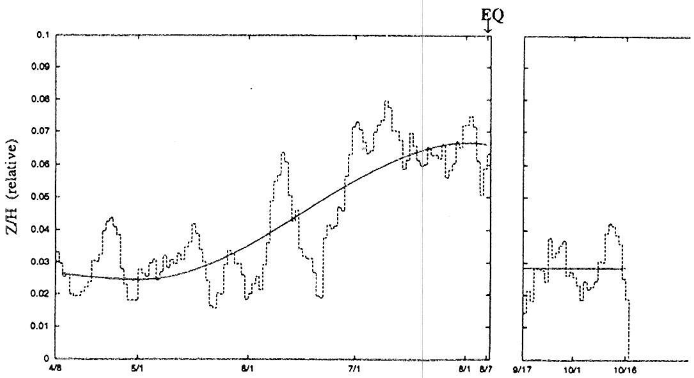

Figure 5. Temporal evolution of the polarization ratio (Z/H) during the whole period. 5 days running mean is used in the plot. A full line indicates the overall general trend estimated by the least squares fit.

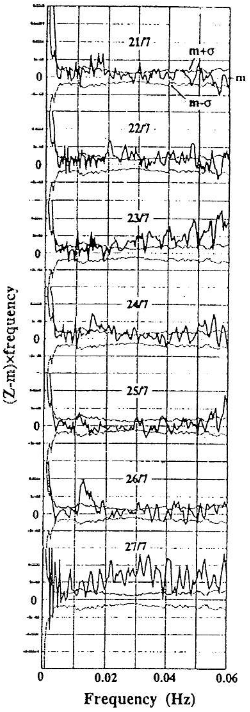

Figure 6. Sequence of frequency spectra (one day average) during 21 $\sim$ 27 July, for which the emissions are probable to be earthquake-related.

on a least squares fit. As is easily understood from this figure, the value itself is considerably reduced by averaging as compared with those in Fig.4. It is clear from this figure that the ratio of Z/H takes, generally, an enhanced maximum during a period starting in the end of June and this general broad maximum is found to persist for about one month until the time of the main shock. Then, after the intermittent observation period after September 17, the ratio is found to be just as before July. So, this broad maximum in Z/H from the end of June to the time of the main shock, may be a strong indication of magnetic precursors of the earthquake. Unfortunetely, the statistical significance of the broad maximum cannot be assessed because of the limitations of the data to six months of observations. Especially, the intervals 5 and 6 from July 22 to August 3 are geomagnetically very quiet, and so the emissions during these intervals may be earthquake-related. Also, a combined consideration of Fig.5 and 2, might indicate that the ULF wave activity in the former half of July is earthquake-related.

Fig.6 illustrates the sequence of ULF wave spectra during the interval 5, especially from July 21-27, which is highly probable to be ULF signatures of the earthquake. We indicate the spectra (average for each day) only for the Z component which is more important for seismogenic emissions than the D component. As seen from this figure, the emission can be considered to be of a noise-like nature (between two types (noise-like and quasi-sinusoidal) by Kopytenko et al. (1994)) and it is dominant in the frequency range of 0.01 $\sim$ 0.05 Hz. The maximum intensity in this frequency range is found to be about 0.1 nT.

Discussion

The principal aim of this paper is to see whether there exists any precursor activity of earthquakes (or ULF signatures) or not. In the previous studies by Fraser-Smith et al. (1990) and Molchanov et al. (1992), they have not treated the data by sophisticated statistical analyses. We have proposed rather sophisticated data analyses for the Guam earthquake on 8 August, 1993, and , especially, we have indicated that the polarization, or the ratio (Z/H) is of essential importance in distinguishing between the space plasma waves and other emissions presumably associated with the earthquake. The geomagnetic pulsations during nighttime are Pi2 and Pc4 and others, which are known to be usually H-polarized (Saito, 1969). But, if the source of emissions is situated under the ground, we can expect the ratio (Z/H) ≥ 1, which is found by Kopytenko et al. (1994) using the experimental measurements and also by Molchanov and Hayakawa (1995) based on the theoretical consideration. The analysis method presented in this report, would be very useful for the future analyses even during the periods including high geomagnetic activities. So, the importance of a more sophisticated analysis based on multiple field components would be emphasized (Hayakawa et al., 1993).

We will summarize the essential features of the ULF measurement for the Guam earthquake. (1) A close comparison between the variations ΣKp and ULF wave activity, has enabled us to distinguish between the space plasma waves and other emissions (obviously not space waves). (2) In addition, the temporal evolution of the ratio (Z/H) during the whole period, exhibits a broad maximum from about one month before the earthquake until its main shock. (3) Based on the considerations (1),(2), the emissions observed in July and August until the main shock, might be ULF signatures of the earthquake. (4) The intensity of Z component shows an enhancement (10 days $\sim$ 2 weeks), a subsequent drop and the second peak a few days before the main shock. (5) The emissions during these periods, are just noise-like and their frequency is dominant in the frequency range (0.01 $\sim$ 0.05 Hz), with maximum intensity, $\sim$ 0.1 nT.

We try to compare these characteristics with the former results. Fraser-Smith et al.(1990) have suggested a threshold in magnitude for having the ULF emissions, but Kopytenko et al.(1994) have observed seismogenic ULF emissions even for moderate earthquakes. The magnitude of this Guam earthquake is 7.1 such that it is sufficiently large to excite ULF emissions, though its depth is deeper than the former large earthquakes of Spitak and Loma Prieta. The distance between the epicenter and the field site in our case is less than a critical value of 100 km, which indicates a possibility of detecting ULF emissions for such a large earthquake as in this paper, as based on the experimental facts by Fraser-Smith et al. (1990, 1994), Molchanov et al. (1992) and Kopytenko et al. (1994) and on our recent theoretical estimation by Molchanov et. al. (1995) and Molchanov and Hayakawa (1995). Based on the extensive use of the ratio (Z/H), we feel that it may be highly possible for us to distinguish between space waves and seismogenic emissions. In the case of Loma Prieta earthquake, the geomagnetic activity was relatively quiet (ΣKp < 27) (Fraser-Smith et al., 1990), but our period included several geomagnetic active periods so that we had to distinguish between the two. This distinction might be possible only by the use of our sophisticated data analysis and the ratio (Z/H). By using this ratio, the emissions during the period of a little more than one month before the main shock may be concluded to be associated with the earthquake. Also, the temporal variation of the Z component is found to be very similar to that for the Loma Prieta earthquake (Fraser-Smith et al., 1990), which is successfully interpreted in terms of the space-time model of microfracture progression (Molchanov and Hayakawa, 1995). The emissions during the intervals of 5 and 6 are of noisy nature (following the definition of Kopytenko et al. (1994)) in the frequency range of 0.01 $\sim$ 0.05 Hz, at which the wave was most intensive for the Loma Prieta earthquake (Fraser-Smith et al., 1990). For this earthquake, Mueller and Johnston (1990) have not found any magnetic fields in the frequency f$< 10^{-3}$Hz. We believe that the results in this paper would provide a convincing evidence on the presence of ULF magnetic earthquake signatures.

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